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Thermal-hydraulic effect of wire spacer in a wire-wrapped fuel bundles for SFR

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HIGHLIGHTS

- This paper presents that the wire effect on three-dimensional flow field and heat transfer characteristics in a helically wrapped 7-pin fuel assembly mock-up of the SFR have been investigated.
- The wire spacers locally induce a tangential flow by up to about 13% of the axial velocity.
- Pressure drop value without wire spacer is about 6% less than that with wire spacer over the various range of Reynolds number. The cross flow due to the wire spacer can achieve to enhance heat transfer characteristics up to about 50%.
- We found that the temperature uncertainty of sub-channel is about 5% of temperature difference between inlet and outlet of the test section.

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ABSTRACT

The computational fluid dynamics (CFD) investigation is carried out over the full-scale experimental facility of SIENA's 7-pin fuel assembly using commercial CFD code, CFX. The purpose of this research is to understand the effect of wire spacer on flow and temperature fields in fuel bundle by comparing the CFD analysis with wire spacer and without wire spacer. Thermal-hydraulic phenomena in a fuel bundle have been investigated by Reynolds Averaged Navier-Stokes (RANS) flow simulation based on the shear stress transport (SST) turbulence model. Calculated pressure drop in the fuel bundle agrees well with Cheng & Todreas model. When the turbulent Prandtl number in the CFD analysis is adopted with 0.02, Nusselt number of the CFD analysis results has a good agreement with Mikityuk model, Graber and Rieger model, and Borishanski et al. model. Based on the CFD investigation, the wire spacers locally induce a tangential flow by up to about 13% of the axial velocity. The tangential flow in the corner and edge sub-channels is much stronger than that in the interior sub-channels. The flow with a high tangential velocity is periodically rotating in a period of wire lead pitch. Pressure drop value without wire spacer is about 6% less than that with wire spacer over the various range of Reynolds number. The cross flow due to the wire spacer can achieve to enhance heat transfer characteristics up to about 50%. Furthermore, the wake regions due to helically wrapped wire spacers are developed nearby the counter rotating position of wire spacers. These wake regions have the peak temperatures in the sub-channels. In this analysis case, we found that the temperature uncertainty of sub-channel is about 5% of temperature difference between inlet and outlet of the test section.

1. Introduction

The SFR (Sodium-cooled Fast Reactor) system is one of the nuclear reactors in which a recycling of transuranic waste by reusing spent nuclear fuel sustains the fission chain reaction. This situation strongly motivated the KAERI (Korea Atomic Energy Research Institute) to start a PGSFR (Prototype Gen-IV Sodium-cooled Fast Reactor) design project under the national nuclear R&D program. Generally, the SFR system has a tight package of the fuel bundle and a high power density. The sodium material has a high thermal conductivity and boiling temperature than the water. That can make core design to be more compact than LWR (Light Water Reactor). The fuel assembly of the SFR system consists of long and thin wire-wrapped fuel bundles and a hexagonal duct, in which wire-wrapped fuel bundles in the

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Nomenclature

A	axial average flow area [m^2]
C_f	friction factor constant defined in Eq. (3) [–]
D_e	equivalent hydraulic diameter [m]
D_r	rod diameter [m]
D_w	wire diameter [m]
F	friction factor [–]
H	wire spacer lead pitch [m]
N	number of each kind of sub-channel in the bundle [–]
N_r	number of fuel pins [–]
Nu	Nusselt number [–]
P	pin pitch [m]
P_t	rod pitch for wire-wrap configuration [m] = $D_r + 1.044 \times D_w$
Pe	Peclet number[–]
Pr	Prandtl number [–]
Re	Reynolds number [–]
S_t	total wetted perimeter [m]
X	X coordinate [m]
y^+	Y plus value [–]
Y	Y coordinate [m]
Z	Z coordinate [m]
μ	dynamic viscosity [N s/m^2]
Ψ	intermittency factor [–]

Subscripts

i	1, 2, 3 or b denote interior, edge, corner sub-channel type, or bundle average, respectively
f	denotes friction factor [–]
l, L	denotes laminar flow region
t, T	denotes turbulent flow region

hexagonal duct has triangular array. The main purpose of a wire spacer is to avoid collisions between adjacent rods. Furthermore, a vortex induced vibration can be mitigated by wire spacers. The wire spacer can enhance a convective heat transfer due to the secondary flow by helically wrapped wires.

The complex flow phenomena in SFR fuel bundle on account of existence of wrapped wire increased the need for thermal-hydraulic research. For entire fuel bundles, many correlations on pressure drop and heat transfer have been developed through experiments (Rehme, 1973; Engel et al., 1979; Cheng and Todreas, 1986; Mikityuk, 2009; Graber and Rieger, 1973; Borishanski et al., 1969; Subbotin et al., 1964). The channel mixing between sub-channels due to wire was also investigated from the micro view (Todreas and Turi, 1972). However, as measurement of thermal-hydraulic characteristics in the fuel bundle was hard because of complex geometry, experiment was limited to measurement of temperature at the wire and wall of rods in some points and intrusive measurement of velocity in the sub-channels (Todreas and Turi, 1972; Roidt et al., 1980).

Recently, the development of computational performance and numerical analysis enabled computational fluid dynamical study of SFR fuel bundles. Many researchers of Pointer et al. (2008), Ahmad and Kim (2006), Jeong et al. (2017), and Gajapathy et al. (2007) performed CFD simulations on the various number of fuel bundles from 1 to 217 to investigate detailed thermal-hydraulic phenomena in the fuel bundle. These researchers found that the flow in the fuel bundle varies axially and laterally according to the relative position of wire and the thermal energy were dispersed uniformly.

When generating meshes, the helically wrapped wire spacer makes it difficult to describe the point-contact geometry between rod and wire spacer. The simplification is to describe the wire as square or polygonal or extend the area between rod and wire (Bieder et al., 2010). However, in order to insure a correct modeling the meshes in the contact region between rod and wire spacer, a shape on the contact region should be sustained without displacement.

The effect of flow and heat transfer characteristic by wire spacer is investigated in detail through numerical simulation by previous researchers. To calculate very detailed thermal-hydraulic properties in the contact region between wire and rod, they isolate single rod with wire spacer. Sreenivasulu et al. Sreenivasulu and Prasad (2009) calculated the flow and heat transfer characteristics in isolated wire-wrapped rod with SST turbulence model. They reveal the velocity, pressure, and temperature fields around the wire-wrapped rod and find the possible hot-spot zones. Ranjan et al. (2011) and Merzari et al. (2012) performed Direct Numerical Simulation (DNS) and Large Eddy Simulation (LES) for the region around single wire. Ranjan et al. observed the variance of temperature field according to Prandtl number and found the reattachment points. Merzari et al. focused on the prediction of the hot spot in conjugate with heat transfer calculation.

Previous researchers also found that the number of rods is not sensitive to thermal-hydraulic flow characteristic of flow in wire-wrapped fuel bundle. Rolfo et al. (2012) conducted the CFD calculation for 7, 19, 61 and 271-pin bundle. As a result, friction factor calculated from CFD result agreed well with simplified Cheng and Todreas model. They also show that Nusselt numbers consistently follow Mikityuk model (Mikityuk, 2009). The consistency slightly increases with number of pins. Gajapathy et al. (2009) performed CFD analysis for 7, 19, 37-pin bundle. They reached to same conclusion that the mean peripheral zonal velocity slightly increase with pin number. Additionally, average difference of temperature between central zone and peripheral zone kept 18 K whether number of pins. Therefore, thermal-hydraulic phenomena in wire-wrapped fuel bundle can be investigated with geometry of small number of pins.

In this study, the wire effect on three-dimensional flow field and heat transfer characteristics in a helically wrapped 7-pin fuel assembly mock-up of an SFR (Sodium-cooled Fast Reactor) have been investigated through a numerical analysis using the commercial CFD (computational fluid dynamics) code, CFX. Complicated and separated flow phenomena in the 7-pin fuel assembly without wire spacer and with wire spacer were captured by a RANS (Reynolds-Averaged Navier-Stokes) flow simulation with the SST (shear stress transport) turbulence model.

2. Numerical analysis methodology

2.1. Test section

A numerical study of the 7-pin fuel assembly was carried out in the sodium boiling and fuel failure propagation test loops (SIENA) installed at PNC's Oarai engineering center. Fig. 1 shows a schematic of the test section and a cross sectional view of the fuel assembly with wire spacers. As shown in diagram, an electrically heated 7-pin bundle was centered in a hexagonal duct, with a 23.6 mm flat-to-flat distance inside. The heated pins were 6.5 mm in diameter with 0.55 mm cladding thickness, arranged in a triangular array with a pin pitch of 7.9 mm, and had a 450 mm heated length. 7 pins of 6.5 mm in diameter were